SPECIAL TECHNICAL REPORT NO. 21

RELIABILITY DEMONSTRATION USING OVERSTRESS TESTING

30 July 1965

Prepared for
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
under Contract NAS8-11087

ARINC RESEARCH CORPORATION
A SUBSIDIARY OF AERONAUTICAL RADIO, INC.

Publication 294-24-24-505

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ABSTRACT

This report presents a new approach to accelerated testing. The approach consists of testing several components to failure in an overstress condition and extrapolating the failure data obtained to the usage condition.

While the proposed method is not an ultimate solution to the problem of reliability demonstration with few samples, it does represent an initial step in the direction of solving overstress testing problems. Its principal advantage is the time it saves. An analysis of test data shows reductions in test time by factors of from 3 to 2000 compared to that which would be required by testing at operational stress levels.

In addition to the proposed test approach, this study reports the results of a search of related literature, including a description of the present state of the art in accelerated testing, an annotated bibliography of prominent documents in the field of accelerated testing for reliability, and some experimental results from tests reported in the literature.

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1. INTRODUCTION

Throughout industry, the demonstration of the reliability of mechanical or electro-mechanical components within the constraints of time and money has posed an increasingly difficult problem. With the advent of the space age, the need for a practical solution to this problem has become acute.

The statistical theory behind reliability demonstration is relatively simple. If there were no limits on test time or money, demonstration of reliability would be easy. The problem arises because of the need to demonstrate reliability quickly and economically.

This report presents an approach to accelerated testing to demonstrate reliability based upon tests-to-failure of overstressed components. ("Overstress" is used in this report as any stress level above that to which the component is expected to be subjected during normal operation.) The data from actual tests-to-failure are used to extrapolate a failure curve to the mission or expected operating environment level, thereby permitting predictions about the probability of the components successfully operating for a specified time.

The theory proposed herein is based on hypotheses which were suggested by the fatigue curves used in the analysis of structural materials. In an attempt to either prove or disprove these hypotheses, test data available in the literature were analyzed. ARINC Research found that the data support the theories advanced, but very little statistical confidence can be placed in the results. However, the method does provide the test engineer with an intuitively sound engineering approach to overstress reliability demonstration testing.

2. SURVEY OF THE STATE OF THE ART

To determine the current methodology and philosophy behind accelerated testing, ARINC Research studied the existing literature and found that many of the proposed techniques never developed past the conceptual phases. The primary reason for this lack of development is the absence of adequate sample sizes from which to determine failure distributions with any degree of confidence. Frequently, however, some form of accelerated life testing is used to assess component reliability. In principle, accelerated testing is designed to determine, through overstress of one or more environmental factors, the actual times-to-failure of a component in less time or with less samples than would be necessary in a conventional reliability test. These testing methods frequently employ an acceleration factor, usually defined as the ratio of the MTBF at the accelerated condition to the MTBF at the mission level. This is usually obtained for various types of components. However, correlation between the accelerated condition and the usage condition presents several problems.

One problem is that the failure modes in the accelerated environment may not be the same as those that occur when the component is functioning in its mission environment. An example of this difficulty has been observed in a study of communications receivers in which operation at high line voltages caused rapid failure of audio-output tubes, while operation at low line voltages caused failure of RF oscillators. A second problem is that small errors in measurement of the accelerated environments can cause large errors in the acceleration factor.

Abstracts, with pertinent comments, of the six documents which ARINC Research considers to be the most significant in the area of overstress testing are included in Appendix A. Section 3 describes the proposed approach to overstress testing to demonstrate reliability.

3. AN ACCELERATED TEST APPROACH

3.1 General

This section outlines an approach to accelerated testing of components which attempts to maximize the amount of useful information obtained from a test. The approach parallels other overstress techniques in that the stress levels used for the test are greater than the mission stress level. However, the approach outlined here does not depend upon acceleration factors as do some of the methods presently employed.

The accelerated testing technique to be outlined here was suggested by the so-called S-N curve (stress amplitude versus the number of cycles-to-failure) which is frequently encountered in the field of fatigue. This curve is generally of the shape shown in Figure 1. Note the endurance limit, which is the stress level below which the time or number of cycles to failure increases indefinitely; i.e., no failures will be experienced below this level.

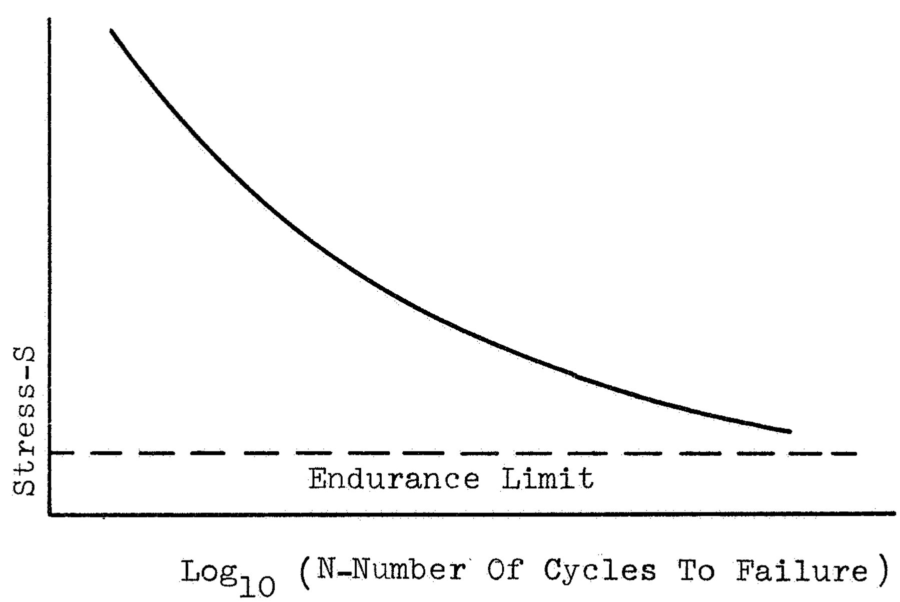

FIGURE 1
TYPICAL S-N CURVE

It might be reasonable to expect this same type of general curve (an increase in N for a decrease in S) to be applicable to the failure of components subjected to such stresses as vibration, temperature, and pressure. Limitations to application of this type of curve may exist, such as the number and types of failure modes involved; however, acceptance that such a curve exists is almost intuitive.

If a series of tests-to-failure are conducted at various stress levels, a failure curve can be obtained by plotting the test stress level on the ordinate and the time- or cycles-to-failure on the abscissa. The graph in Figure 2 represents such a failure curve.

FIGURE 2

TYPICAL FAILURE CURVE

The method proposed in this report is based on the following hypotheses which were suggested by the above failure curve:

1) There exists a component failure curve which can be determined by overstress testing.
2) The slope of the failure curve becomes less negative as the stress level is decreased (life, N, increases as stress, S, decreases).

These hypotheses must be verified by the life testing of several types of components before they can be used with any confidence.

If the hypotheses can be at least partially substantiated, a technique can be developed whereby at least a conservative value of a reliability parameter, such as the estimated mean of the component life, can be demonstrated with less test time than that usually required.

Suppose the actual failure curve of a component is determined by plotting the average times-to-failure of four samples at each of four stress levels, S_1 through S_4, as shown in Figure 3. The X's on this graph represent the times-to-failure of identical components tested at various stress levels. If the curve shown is found to have the same general shape for various types of components, then the proposed method of accelerated testing could be employed. Note that the nature of the data is such that it is more convenient to plot the logarithm of the time or cycle variable than to plot the variable itself.

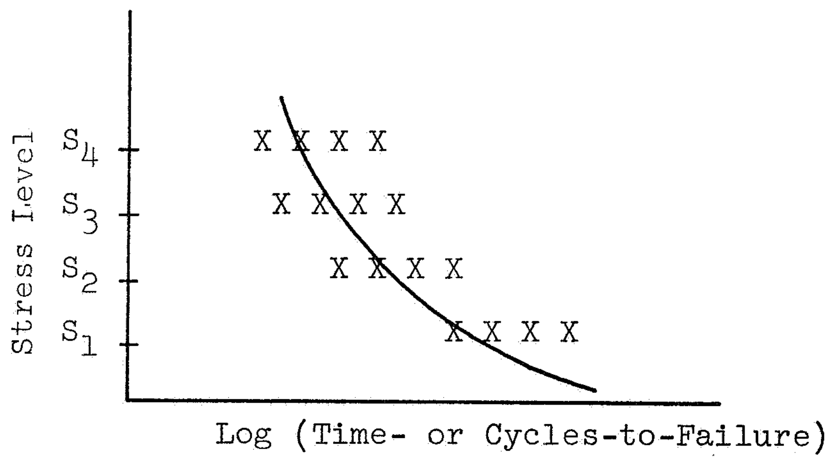

FIGURE 3

ACTUAL FAILURE CURVE

3.2 Description of Approach

For this example, the assumption is made that the sample size is approximately the same as that normally used in the procurement specification (i.e., four to eight samples). From these samples it is impossible to describe the distribution from which they came. However, an estimate of the mean life at each stress level can be obtained and the failure curve can be plotted.

Let us next assume that S_1 is the mission level or anticipated stress level which the component would be expected to survive during use (Figure 4). If a life test is performed at the mission stress level (S_1), a mean life or an estimate of the mean-time-to-failure (θ_1) can be determined.

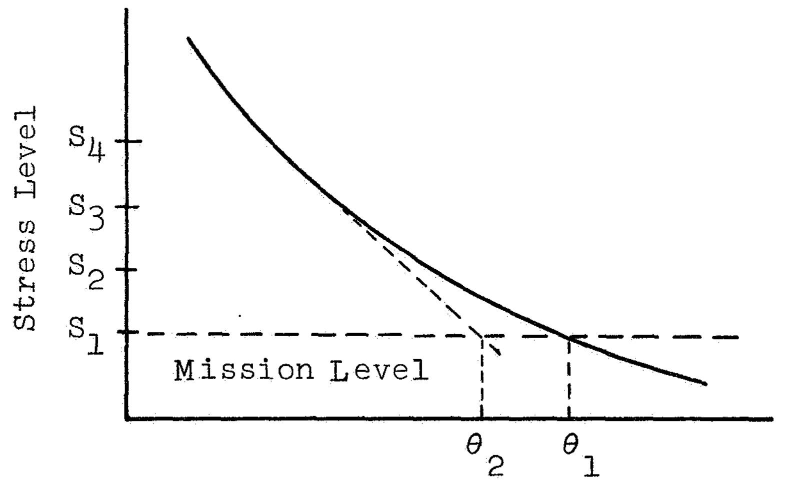

FIGURE 4
EXTRAPOLATION OF FAILURE CURVE

The test time necessary to arrive at this mean-time-to-failure is the number of components tested multiplied by the mean-time-to-failure (θ_1).

In the method proposed, the procedure consists of testing half the number of the available identical components to failure at each stress level, S_3 and S_4. The average- or mean-time-to-failure at each of these stress levels is determined and a straight line drawn through these points and extrapolated to the mission level. The intersection of the extrapolated line with the mission level corresponds to an estimated mean life (θ_2) at the mission level. Then θ_2 is used as an estimate of the mean-time-to-failure at the mission level. This estimate is conservative as long as the conditions stated in the hypotheses are true. The test time necessary to demonstrate the estimate of the mean-time-to-failure at the operating level is obtained by summing the times-to-failure of the components tested at S_4 and the times-to-failure of the components tested at S_3.

4. DATA ANALYSIS

In order to evaluate the proposed testing technique, an analysis of typical test data obtained from the literature is presented. The total test time required to perform a test-to-failure at the mission level is compared to the total test time required to predict the time-to-failure at the same level by using the proposed technique. A detailed description of the tests, the test data, and the analysis is presented in Appendix B.

4.1 Data Description

The data were obtained from the literature search and consist of results of tests-to-failure on identical components at several environmental levels. Data from tests-to-failure were obtained for ten different components, including a limit switch, some major structural components of a fighter aircraft, aluminum panels, and lead supported resistors.

The tests-to-failure of the various components were conducted in different environmental or operating conditions, labeled as stress levels. The limit switch was tested to failure using current as the stress, the aircraft structural components were tested to failure using percent of design load as the stress, and the lead supported resistors were tested to failure using vibration as the stress. Some of the data are in terms of time-to-failure; other data are in terms of cycles-to-failure.

The available data were reviewed for types of failures which occurred. This information was not available for some components. The information that was available is included in Appendix B. For example, 12 failures of the airplane wing occurred at 4 different places, 10 of the 12 failures occurred at 3 different wing-fuselage attachments and 7 of these 10 failures occurred at the same attachment.

4.2 Analysis

The collected data were analyzed in the following manner.

Times-to-failure at the actual mission level were predicted using both the actual component failure curve and the hypothesized straight line technique. These times were designated on the plotted curves as θ_1 and θ_2, respectively (see Figure 5).

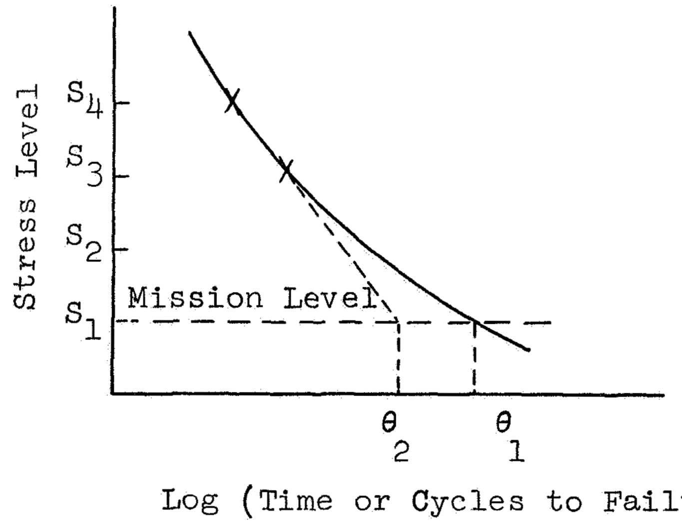

FIGURE 5

The mean-time-to-failure at the mission level (θ_1) as determined by the actual failure curve can be read directly from the various load-versus-log (time-to-failure) curves. The mean-time-to-failure as predicted by the hypothesized straight line technique, θ_2, can be determined by solving the equation of the straight line which passes through the mean-times-to-failure at the accelerated test stress levels, S_2 and S_3 (Figure 5), for θ_2. This procedure leads to the following expression for θ_2:

$$\log_{10} \theta_2 = \frac{S_3 - S_1}{S_3 - S_2} (\log_{10} t_2 - \log_{10} t_3) + \log_{10} t_3$$

where,

S_1, S_2, and S_3 are the stress levels

t_2 is the test time at S_2

t_3 is the test time at S_3

θ_2 is the predicted mean time between failures at S_1

In the plots of experimental results (Appendix B), the upper two stress levels are taken to be the accelerated test stress levels. Knowledge of θ_1 and θ_2 allows a measure of the conservatism of the straight line hypothesis. This is done by forming the ratio ${}^{\theta_1}/_{\theta_2}$, which increases as the prediction becomes more conservative.

In an attempt to demonstrate how much test time the hypothesized test method would save, an arbitrary method of comparison was devised. This method assumed that eight samples were available for testing. If all eight of these samples were tested at the mission level, the total test time would be

$$T_1 = 8\ (\theta_1)$$

If four samples are tested at each of the accelerated test stress levels (S_3 and S_4 in Figure 5) then the total test time will be

$$T_2 = 4\ (t_2 + t_3)$$

From T_1 and T_2 the ratio ${}^{T_1}/_{T_2}$ can be formed. This ratio is a measure of the time saved by using the hypothesized test method.

4.3 Results

The results of this analysis are summarized in Table 1. This table presents the type of test conducted, the mean-cycles-to-failure at the mission level as obtained by the actual failure curve (θ_1) and as predicted by the hypothesized straight line technique (θ_2), the ratio of θ_1 to θ_2, the number of test cycles (T_1 and T_2) to demonstrate the mean-cycles-to-failure for each method and the ratio of test times (T_1/T_2).

The ratio θ_1/θ_2 indicates the conservatism of the predicted mean obtained by the straight line technique over that obtained by the actual failure curve, and the ratio of test times (T_1/T_2) measures the test cycles saved by using the straight line technique. For example, the data for the acoustical fatigue test of the aluminum panels gives a ratio of $\theta_1/\theta_2 = 1.62$; this means that the mean-time-to-failure obtained from actual data is 1.62 times that predicted by the straight line technique. The corresponding ratio of test cycles, $T_1/T_2 = 179.9$, means that the number of test cycles required to obtain the mean-cycles-to-failure from actual data requires 179.9 times as many test cycles as that required to obtain the predicted mean-cycles-to-failure by the straight line technique. Thus, 179.9 times as much testing demonstrates a mean which is greater by a factor of 1.62. The ratios of the means varied from 1.10 for the limit switch to 99.34 for the sheet coupons, and the ratio of the test cycles varied from 3.1 for the limit switch to 2030 for the bonded joints. In all cases, however, the savings in test cycles was greater proportionately than the conservatism which was common in the use of the straight line technique.

TABLE 1

COMPARISON OF TEST RESULTS

Test	Mean Cycles to Failure (From actual data) θ_1 Cycles	Mean Cycles to Failure (straight line technique) θ_2 Cycles	Ratio of Means θ_1/θ_2	Number of Test Cycles (8 samples) T_1 Cycles	Number of Test Cycles (8 samples) T_2 Cycles	Ratio of Test Times T_1/T_2
Acoustical Fatigue (db) Aluminum Panels	51.1	25.2	1.62	568.7	31.6	179.9
Vibration Fatigue (g's) Resistor	1.55×10^6	4.91×10^4	31.57	1.24×10^7	1.33×10^5	93.2
Fatigue (% Design Limit Load) Horizontal Tail	5.59×10^4	5.60×10^3	10.0	4.48×10^5	2.55×10^3	175.7
Fatigue (% Design Limit Load) Airplane Wing	1.49×10^5	4.49×10^5	3.34	1.20×10^6	1.15×10^4	104.5
Fatigue (% Design Limit Load) Vertical Tail	4.52×10^4	8.11×10^3	5.55	3.60×10^5	9.40×10^3	38.3
Load Cycling (Amperes) Limit Switch	3.42×10^4	3.16×10^4	1.10	2.73×10^5	8.95×10^4	3.1
Fatigue (ksi) Sheet Coupons	8.14×10^5	8.20×10^3	99.34	6.51×10^6	2.06×10^4	315.6
Fatigue (ksi) Bonded Joints	1.21×10^7	1.79×10^5	67.4	9.65×10^7	4.78×10^4	2.02×10^3
Fatigue (psi) L65 Lugs	5.60×10^6	1.07×10^6	5.23	4.48×10^7	1.04×10^6	43.24
Fatigue (% Design Limit Load) Composite Beam	8.57×10^4	5.19×10^4	1.65	6.86×10^5	3.40×10^4	20.14

This analysis permitted the following observations, common to all the components.

1) The data substantiated the hypothesis that for each component a failure curve exists that has a slope which becomes less negative as the stress level decreases.

2) All ratios of means indicated conservatism and all ratios of test cycles indicated that a savings in testing resulted by using the straight line technique.

5. APPLICATION OF PROPOSED TESTING TECHNIQUE

5.1 Example

The proposed testing technique described in the previous sections can be applied readily to the reliability assessment of components, provided the assumptions and hypotheses are proven valid. Partial justification of the hypotheses was obtained by analysis of the limited data used in this report. More complete verification would necessitate evaluation of similar data for components in general, including valves, relays, etc. These data will naturally become available as time progresses or as the result of testing to verify the stated hypotheses of proposed testing techniques.

An example is presented to illustrate the potential use of the test approach in performing a reliability demonstration test. It is assumed that there is a functional description of the component, a specified test environment and test criteria, and a defined test plan. The following information is assumed to be available:

(1) The reliability goal is specified by contractual documents as 0.9995 for the component while functioning in its normal mode of operation for a mission time of 10 minutes.

(2) The criteria for success or failure of the component have been established in terms of performance parameters and quantitative limits.

(3) The significant environments which are to be considered as part of the life testing have been determined -- if possible by factorial analysis and testing during component

development. The vibration and temperature environments are critical for this example and the anticipated mission will not exceed a maximum vibration of 15 g's and a maximum temperature of 200°C.

(4) The test facility is capable of testing the component while it is functioning in its normal mode of operation and being subjected to the desired environments. We assume for this example that the test facility is capable of testing the component in its normal operating mode at a vibration level of 50 g's and a temperature of 200°C.

The type of test for this example is a sinusoidal vibration test at a temperature of 200°C. We assume that a sinusoidal sweep test has been performed on the component in order to determine the most severe resonant frequency for the most critical axis.

Several components are tested at two over-stress levels of vibration. The selection of these levels is arbitrary, but the levels must be within the capabilities of the test facilities and low enough so that the component will not fail as soon as the level is imposed. The levels used in this example are 50 g's and 40 g's. At the first level the required number of components are tested to failure at a vibration level of 50 g's and at a temperature of 200°C. At the next level, the required number of components are tested to failure at a vibration level of 40 g's and at a temperature of 200°C. For this example, we assume that four samples were tested to failure at each level and a mean value was calculated from the data at each level. Assume that the mean values thus calculated were found to be 50 hours at the 50-g level and 96.5 hours at the 40-g level. These values are plotted as shown in Figure 6.

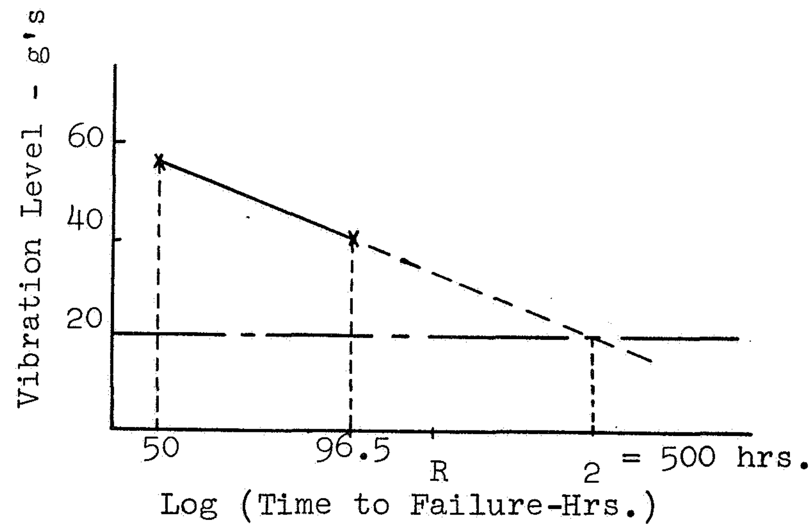

FIGURE 6

EXTRAPOLATION CURVE

The line drawn between the mean values at these two levels is extrapolated to the mission level. The intersection of this line with the mission level is shown as θ_2, which is the best estimate of the actual MTBF of the component. This estimate, calculated by using the equation in Section 4, is determined to be 500 hours.

The MTBF as estimated from the overstress test can be compared with the required MTBF (θ_R) for this component. The required MTBF is obtained in he conventional manner from the specified reliability goal of 0.9995 by assuming a exponential distribution of failures. This results in a required MTBF for this example of 333.3 hours. Since the estimated MTBF (θ_2) of 500 hours is greater than θ_R, the reliability requirement has been met. If the estimated value (θ_2) is less than the required value (θ_R), a decision would have to be made concerning the required action. There are at least three alternatives:

(1) Accept the component with an estimated MTBF less than that required.

(2) Test more samples at a lower stress level (for this example, more testing might occur at the 20-g level) to better define the failure curve.

(3) Redesign the component partially or completely and retest.

In the example just presented, a comparison of test times can be made from the results of the test program. On the basis of 8 samples, 4 at each of the 50- and 40-g levels, the test time required to demonstrate the estimated MTBF of 500 hours using the overstress test method is a total of 4 × 50 plus 4 × 96.5 or 586 hours. To demonstrate the required MTBF of 333.3 hours using the conventional test method at the mission level with 8 samples would require a total test time of 8 × 333.3 or 2666 hours. For this example, 2080 hours of test time could be saved.

5.2 Limitations

In the hypothetical example which was just illustrated the environmental stresses chosen were sinusoidal vibration and temperature. Other environmental factors such as random vibration and temperature could have been used.

In this example, the sinusoidal vibration environment was the overstress condition while the temperature remained constant. However, the temperature environment could have been the overstress condition while the vibration level remained constant. It may also be possible to use two overstress conditions simultaneously as both vibration and temperature levels at a higher level than anticipated during the mission.

These overstress environments should be applied with caution. The hypothesis as stated previously should be verified. whether one or more overstress conditions are to be applied. Overstress conditions such as high temperatures which might cause breakdown of the material of the equipment and result in a change of failure mode could be detrimental to the test program.

It is necessary to distinguish between operating load and environmental condition as the stress level in developing this type of accelerated test approach. Theoretically, the test could be performed either by applying an operating load such as voltage or pressure as the overstress condition or by applying an environmental condition such as vibration or temperature as the overstress condition. Careful consideration should be given to determining the type of overstress which is to be applied. The overstress condition to be used will depend on the operating loads and environmental conditions which the component is to be subjected to in use as well as the capabilities of the test facilities. An engineering trade-off study would determine which overstress condition would be the most practical.

6. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are based on the findings of this study:

(1) Accelerated testing techniques currently using acceleration factors (Ratios of MTBF at two environmental levels) are restricted because:

(a) Differences in failure modes caused by changes in environments have a significant effect on acceleration factors.

(b) Small errors in measurements of the environments have a large effect on acceleration factors.

(2) The proposed overstress testing approach appears feasible. The limited amount of data available verified the hypotheses upon which the method proposed herein is based.

(3) Some of the data which were collected and analyzed exhibited more than one mode of failure. This did not appear to have any significant effect on the proposed testing approach.

Based on this study, it is recommended that:

(1) The proposed overstress testing approach be considered as a reliability assessment technique which can reduce the time required to test components.

(2) The study be continued to investigate more completely and verify the proposed testing approach. Additional test data should be collected and overstress failure data on various types of components should be analyzed.

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APPENDIX A

REVIEW OF MOST SIGNIFICANT DOCUMENTS

This appendix provides abstracts and ARINC Research Corporation comments on six documents representative of the most significant work done in component reliability prediction from accelerated testing.

AUTHORS

Bush, Thomas L., Anthony P. Meyers, Darwin F. Simonaitis

TITLE

Methods for Predicting Combined Electronic and Mechanical System Reliability (Final Report)

SOURCE

Illinois Institute of Technology Report No. 4 IITRI Project E186, 1963

ABSTRACT

The objective of this program was to develop methods, relationships, and/or guidelines for predicting, during the design stage, the reliability of those types of military equipments which make extensive use of both electronic and mechanical components. A review was made of reliability prediction techniques and data available for electronic and electro-mechanical components. However, the major effort was concentrated on the problem of developing reliability prediction techniques for mechanical parts, upon which a system reliability prediction would be based.

The reliability evaluation methodology developed in this program was based upon the utilization of knowledge on mechanical failure mechanisms and its application to major part failure modes, including the use of available statistical information on failure mechanisms. The major failure mechanisms studied were fatigue and surface fatigue. The principal mechanical parts studied were gears (fatigue and surface fatigue analysis) and rolling contact bearings (using available failure mode and failure distribution data). In addition, the fatigue reliability concept developed for gears was also considered for application to shafts and positive

engagement clutches. A theoretical model for evaluating adhesive wear was also studied; however, more information on several aspects of related mechanical phenomena is necessary before general application of the adhesive wear concept can be made in reliability evaluation. The concepts studied in the program and the reliability prediction technique as developed were then demonstrated in a sample evaluation of an electro-mechanical device, a rotary-drum flight control actuator.

COMMENTS

This report is the last of four prepared by the Illinois Institute of Technology concerning methods for predicting mechanical system reliability. Although it was directed primarily towards predicting in the design stage the reliability of those equipments composed of both mechanical and electronic components, its contribution to the prediction of reliability at later stages is profound.

In this report, the methodology discussed was concerned with the optimum use of current information in building reliability prediction techniques for mechanical and electromechanical components. The work presented in this report represents a major advance towards arriving at such techniques.

AUTHORS

Chernowitz, George, James M. Ciccotti, Angelo W. Castellon, Gerald L. Geltman.

TITLE

Electro-mechanical Component Reliability

SOURCE

APJ Report 309-1, May 1963, Prepared by the American Power Jet Company, Ridgefield, New Jersey

ABSTRACT

The reliability of mechanical and electro-mechanical components is investigated from physical and mechanism-of-failure points of view, with the goal of improved design practice and specification requirements.

Observed failure data on the 413L system are used as the empirical base for phenomenological and physical analysis. Applied model considerations and the implications of assuming given failure distributions are studied; new techniques are given to verify whether observed data are Weibull in form.

Fifteen components applicable to ground electronic systems are studied in detail:

Actuators	Couplings	Potentiometers
Bearings	Electric Components	Relays
Cable	Fasteners	Rheostats
Clutches	Gears	Switches
Counters	Motors	Synchros

For these, a guide is given to pertinent failure mechanisms, critical causes of failure and correlation with experience

data, indicating the relative importance of each cause. Materials, manufacturing variability and the influence of fabrication are covered from both materials and component viewpoints. Current reliability proof requirements and criteria for the preparation of a reliability specification are discussed.

COMMENTS

This report presents an extremely valuable contribution to the little known area of electro-mechanical component reliability. The purpose of the study was to investigate the reliability of mechanical and electro-mechanical components from the physical as well as mechanisms-of-failure points of view, with the goal of improved design practice and specification requirements. Valuable knowledge concerning mechanical and electro-mechanical component behavior is contained within this document.

Several areas which would be of particular interest to those contemplating accelerated tests of mechanical and electro-mechanical components are discussed. Some of these are:

(1) Reasons why the exponential distribution is not applicable for mechanical and electro-mechanical components

(2) Failure modes which sharply distinguish electro-mechanical components from their electronic counterparts

(3) Results of a data search on electro-mechanical components

(4) Results of a 2-year check on the behavior of electro-mechanical components in the 413L system

(5) A variant failure analysis consisting of fitting alternative distributions to data samples of electro-mechanical components

This is a concise report directed primarily toward design practice and specification requirements. It also contains information relevant to accelerated testing, particularly for mechanical and electro-mechanical components.

AUTHORS

Chernowitz, George, Samuel J. Bailey, Angelo W. Castellon, Gerald L. Geltman

TITLE

Reliability Prediction for Mechanical and Electro-mechanical Parts

SOURCE

Technical Documentary Report No. RADC-TDR-64-50, May 1964, Reliability Branch, Rome Air Development Center Research and Technology Division, Air Force Systems Command, Griffis Air Force Base, New York

ABSTRACT

The reliability of selected parts is investigated from the viewpoint of materials' behavior throughout parts-materials history, including process, fabrication, test, handling, and early operation. The parts studied are: Mechanical (bearing and gears), Electro-mechanical (brushes and contacts).

Failure mechanisms were examined on the basis of a "SCWIFT" taxonomy.

S - Stress-Creep Rupture
C - Corrosion
W - Wear
I - Impact
F - Fatigue
T - Thermal

Dominant among the mechanisms of failure were wear and fatigue phenomena.

A multistage process was developed for organizing analytical and empirical investigation of part failure causes in a broader sense, based on materials' influences which may be statistically related to part survival. The definition of a "retrospective part survival function" was proposed.

Data and relationships covering flaw propagation, fracture, corrosion, surface fatigue, and the influence of materials and manufacture are given for the parts studied.

COMMENTS

This report discusses the influences which are significant in determining the life expectancy of mechanical and electro-mechanical parts, particularly brushes, contacts, gears and bearings. Its importance lies in its thorough discussion of those factors which are essential to the prediction of the reliability of components. An example of this is the chapter which recommends an approach to electro-mechanical reliability predictions which provides not only a means of organizing data and making predictions, but of progressively improving the estimate of the underlying distribution.

A section which should be of interest to statisticians and reliability engineers discusses the application of the Weibull distribution to describe the failure pattern of mechanical components. Significant results are presented.

This report should prove helpful to anyone concerned with mechanical and electro-mechanical parts reliability, particularly in the area of prediction.

AUTHOR

Fulton, Donald W.

TITLE

The Reliability Analysis of Non-Electronic Components

SOURCE

Technical Memorandum No. RAS-TM-63-2, March 1963, Applied Research Laboratory, Rome Air Development Center, Air Force Systems Command, Griffiss Air Force Base, New York

ABSTRACT

This report deals with the prediction, estimation and demonstration of the reliability of non-electronics parts from a mechanisms-of-failure point of view. Most reliability work performed in the past has been concerned with electronic items.

Mechanical and electronical components have quite different failure responses. Tests and common observations suggest that failures vary with time, hence a hypothesis of random failure is not a valid one.

Several techniques for predicting mechanical and electro-mechanical component reliability are presented. Lack of maturity in the state of the art in predicting mechanical and electro-mechanical reliability, as well as the scarcity of empirical data in this area, is noted.

COMMENTS

This report does not deal specifically with overstress testing, but contains important information on predicting mechanical and electro-mechanical reliability. The prediction techniques presented are:

(1) The Freudenthal approach to reliability analysis of complex mechanical structures

(2) The analysis by variance method by Robert Lusser

(3) A simplified deterministic approach

The advantages and limitations of each method are discussed. The author directs attention to the work presently being done by the American Power Jet Company in the area of mechanical and electro-mechanical component reliability. He emphasizes the need to overcome many barriers before any appreciable advancement can be made in this area.

AUTHORS

Lipson, Charles, Jal Kerawalla, and Larry Mitchell

TITLE

Engineering Applications of Reliability

SOURCE

The University of Michigan, 1963

ABSTRACT

None

COMMENTS

It would be an extensive project to summarize this report justly. Therefore, an outline containing the seven major topics discussed and those chapters which pertain directly to those topics will be presented. Many areas in addition to those listed below are thoroughly discussed.

Engineering Applications of Reliability

I. Background for Reliability
   A. Introduction to Reliability

II. Tools for Reliability - Statistics
   A. Introduction to Statistics
   B. Continuous Random Variables
   C. Discrete Random Variables
   D. Test for Significance - Single Variables
   E. Test for Significance - Two Variables

III. Tools for Reliability - Fracture Analysis
   A. Failure Analysis
   B. Identification of Fractures

IV. Tools for Reliability - Stress and Strength

A. Stress Analysis

B. Strength Analysis

C. Factors of Safety

V. Reliability Prediction

A. Inference Theory

B. Design Life Factors

C. Design Stress Factors

D. Reliability in Rolling Contact Fatigue

E. Reliability of System

VI. Reliability Verification

A. Design of Tests

B. Accelerated Tests

VII. Reliability in Production

A. Statistical Analysis

B. Tolerance in Production

C. Sequential Analysis

This report deals with the statistical as well as engineering aspects of reliability. A thorough discussion of accelerated testing including small sample size testing is presented. This is probably the most thorough, up-to-date document in the general area of mechanical reliability.

AUTHORS

Winter, B. B., C. A. Denison, H. J. Hietala, F. W. Greene

TITLE

Accelerated Life Testing of Guidance Components

SOURCE

Technical Documentary Report No. ALTDR 64-234, 30 September 1964, prepared by the Autonetics Division of North American Aviation, Inc., Anaheim, California

ABSTRACT

The report deals with theoretical developments necessary for accelerated testing and with specific hardware considerations. In the theoretical area, the currently prevalent approach to accelerated testing is described and analyzed, and is found inadequate. A comparative discussion of various failure models is presented, and those most amenable to meaningful accelerated testing are developed in detail. Models for devices with multiple failure modes are described, and pertinent estimation procedures are reviewed. A new method for efficient estimation of the failure distribution of repairable equipment is presented. In the hardware area, the report includes a detailed examination of several space guidance components, with emphasis on considerations pertinent to accelerated testing. The phenomenon of metallic creep is examined from the standpoint of its relation to failures of space guidance components, and methods of accelerated estimation of creep behavior are examined.

COMMENTS

Accelerated testing (the types with their limitations and feasibility) is discussed in great detail. Attention is focused on the consequences resulting from assuming erroneous failure distributions. The importance of making assumptions when utilizing accelerated test techniques in the areas of selection, prediction,and decision is thoroughly evaluated. The use of failure models and their application to accelerated testing are discussed.

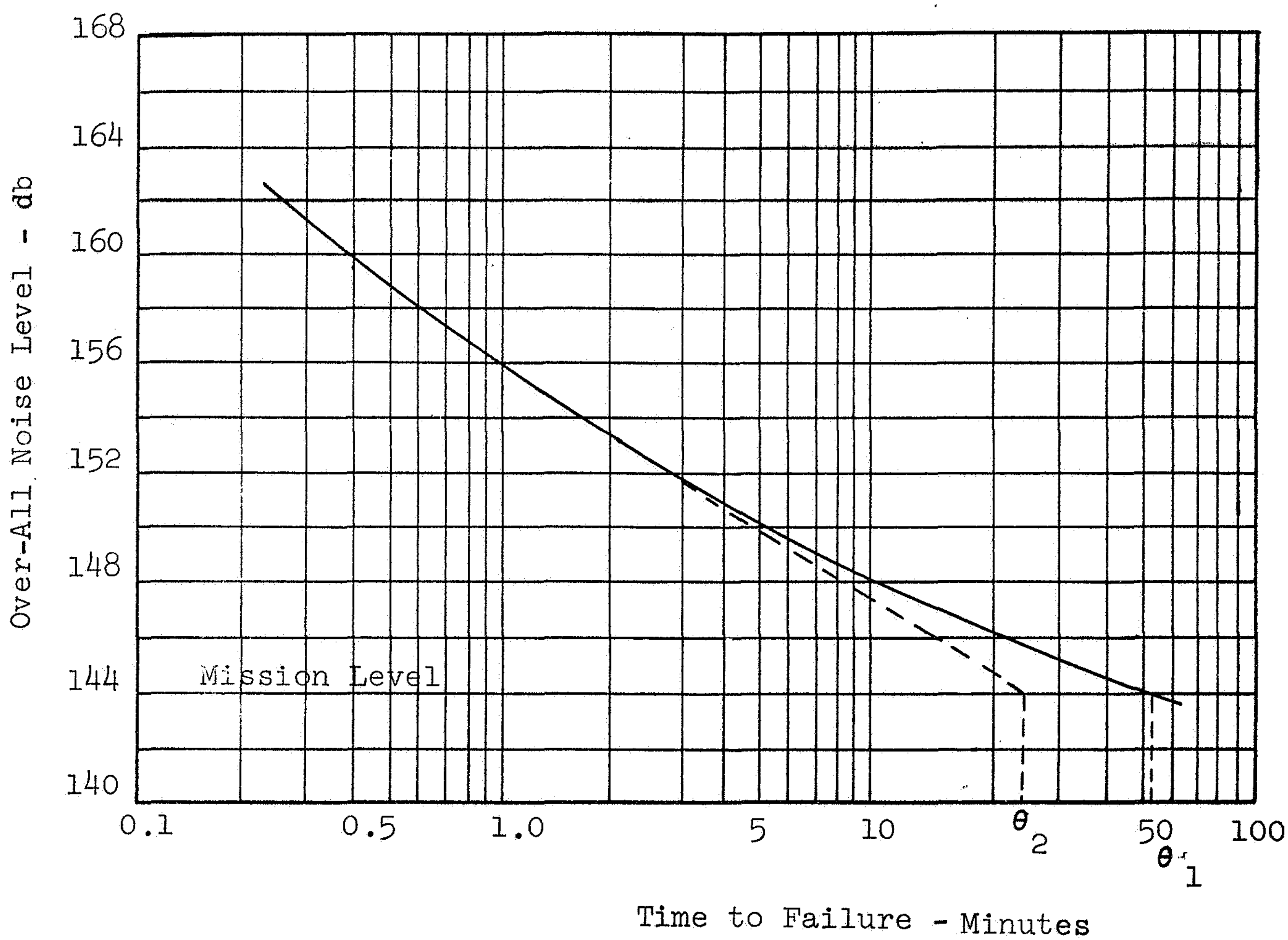
The high point of this report is the section which describes the applicability and feasibility of accelerated life testing of precision electro-mechanical components such as gyros, velocity meters, and servo meters. Although the presentation is mostly theoretical, the information should be valuable to anyone contemplating the use of accelerated testing techniques, particularly on mechanical and electro-mechanical components.

APPENDIX B

VERIFICATION TESTS AND DATA

This appendix describes the tests and the data used to verify the test approach described in Section 3.

ACOUSTICAL FATIGUE TEST TO FAILURE - ALUMINUM PANELS



Test Description

The aluminum panels tested were subjected to acoustical excitation developed by a discrete frequency noise source (siren).

Data

The data were obtained from a graph in the referenced report and consisted of times-to-failure at various over-all noise levels. The mean values of the data are given in the following table:

Over-All Noise Level (db)	Mean Time-to-Failure (Minutes)	Number of Samples
160	0.26	1
157	0.74	10
150	4.95	7
144	51.09	11

The point at 160 db is not considered to be statistically significant since only one sample was tested at that level. This point is not used in the calculations.

Results

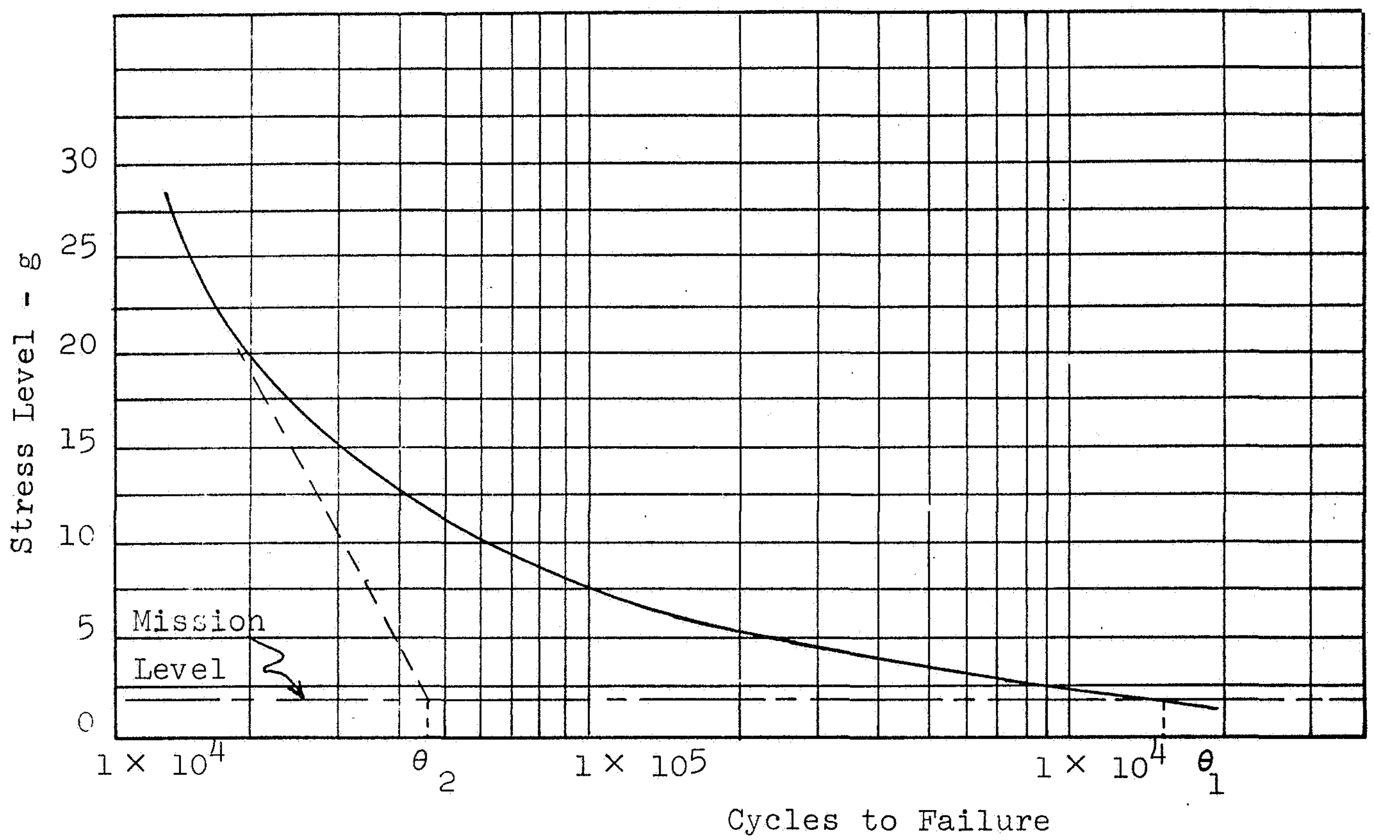
θ_1 = 51.1 cycles; θ_2 = 25.24 cycles; $\theta_1/\theta_2 = 1.62$

T_1 = 568.7 cycles; T_2 = 31.6 cycles; $T_1/T_2 = 179.9$

Reference

"Symposium on Acoustical Fatigue", ASTM Special Technical Publication No. 284, page 55 1960.

VIBRATION FATIGUE TESTS-TO-FAILURE -
LEAD SUPPORTED RESISTOR



Test Description

Resonant vibration tests-to-failure were performed on several sizes of resistors soldered to terminals by standard techniques.

Data

The plotted points represent the means of the number of cycles-to-failure at each vibratory acceleration amplitude (g) which was applied to the base of the components. The data presented here were taken from a plot in the referenced paper. The mean values of the plotted data are presented in the following table.

Vibration Stress Level - g	Cycles-to-Failure	Number of Samples
25	1.44×10^4	5
20	1.88×10^4	5
15	3.56×10^4	7
10	5.30×10^4	4
5	2.33×10^5	8
2	1.55×10^6	4

Results

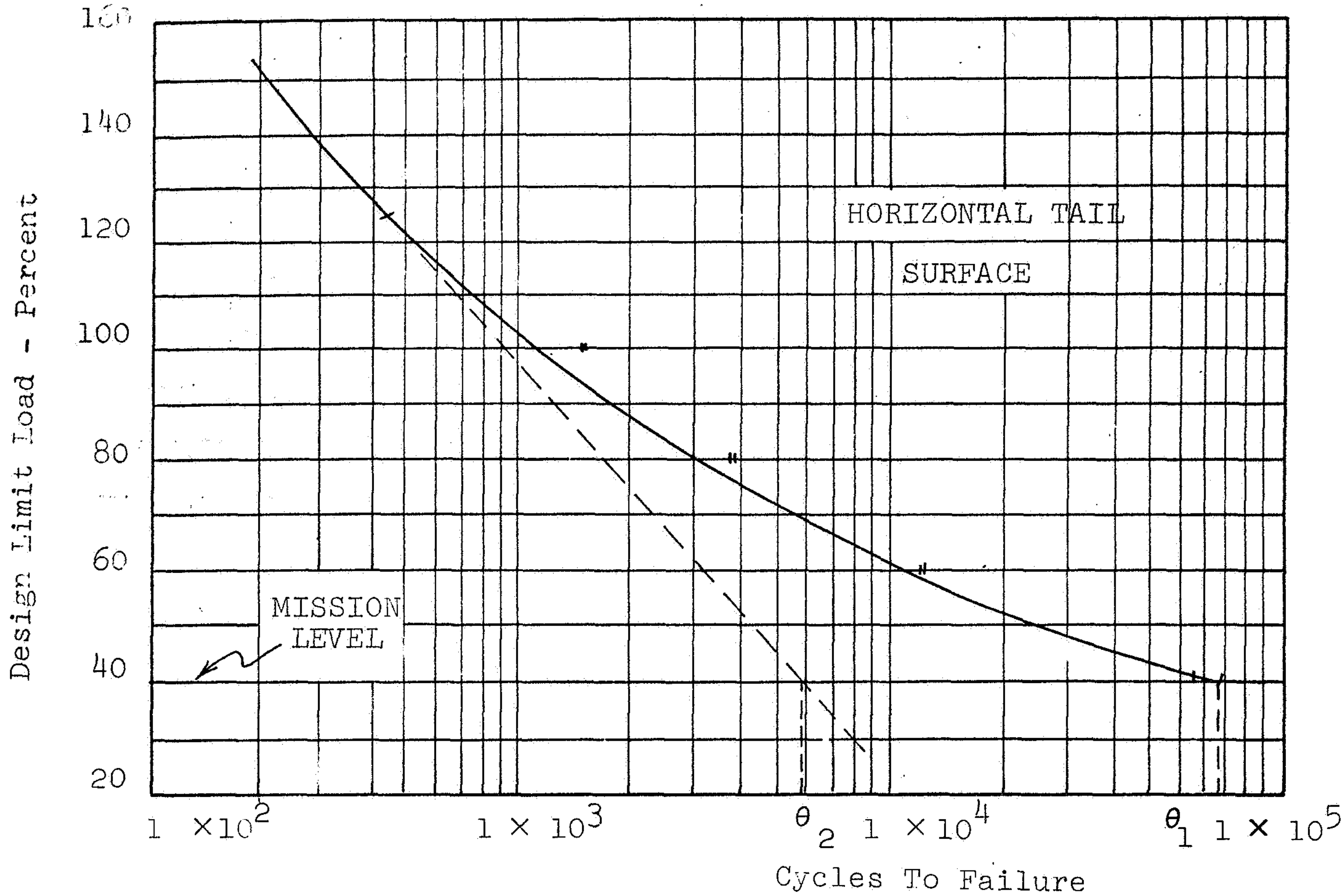
$\theta_1 = 1.55 \times 10^6$ cycles; $\theta_2 = 4.91 \times 10^4$ cycles; $\theta_1/\theta_2 = 31.57$

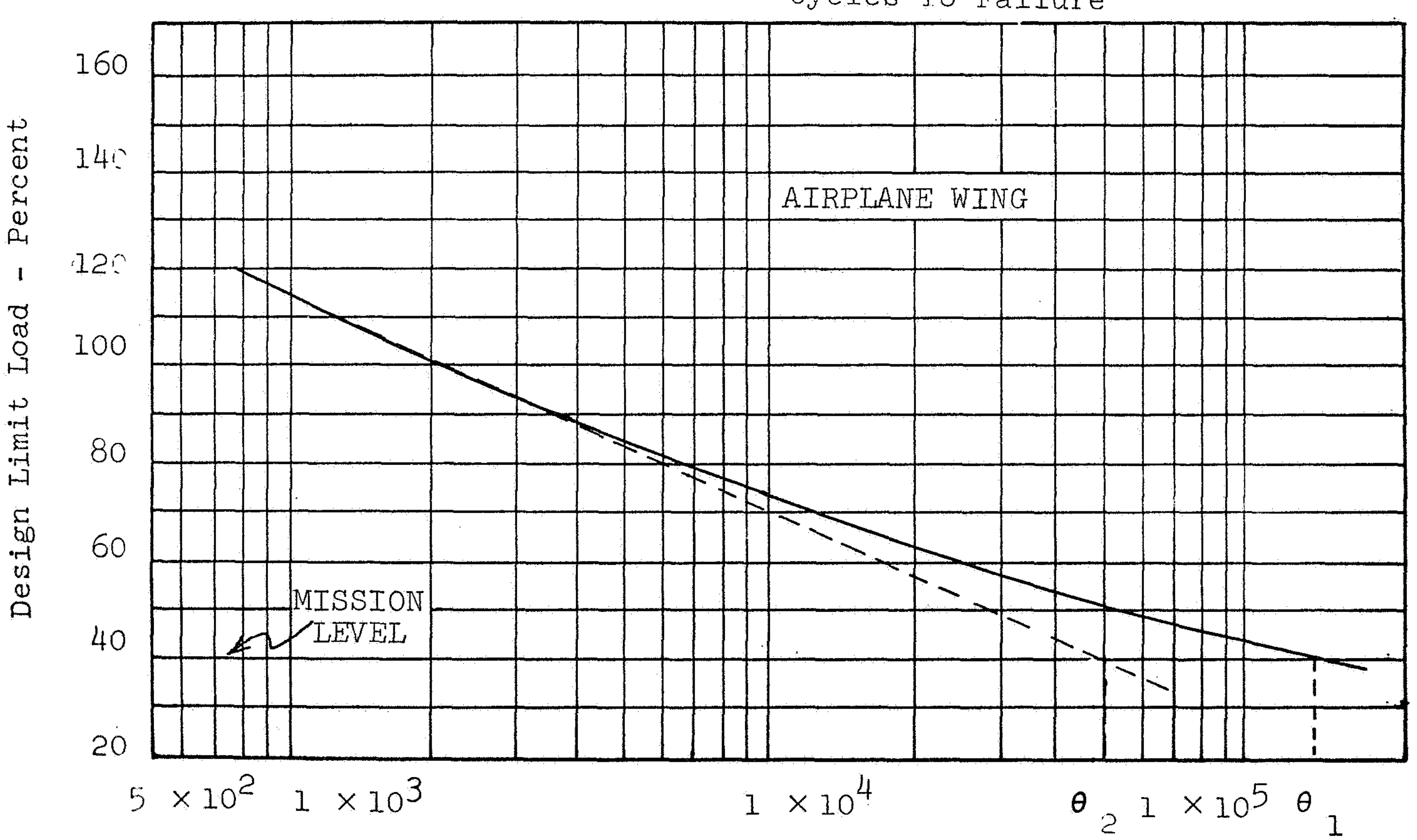
$T_1 = 1.24 \times 10^7$ cycles; $T_2 = 1.33 \times 10^5$ cycles; $T_1/T_2 = 93.2$

Reference

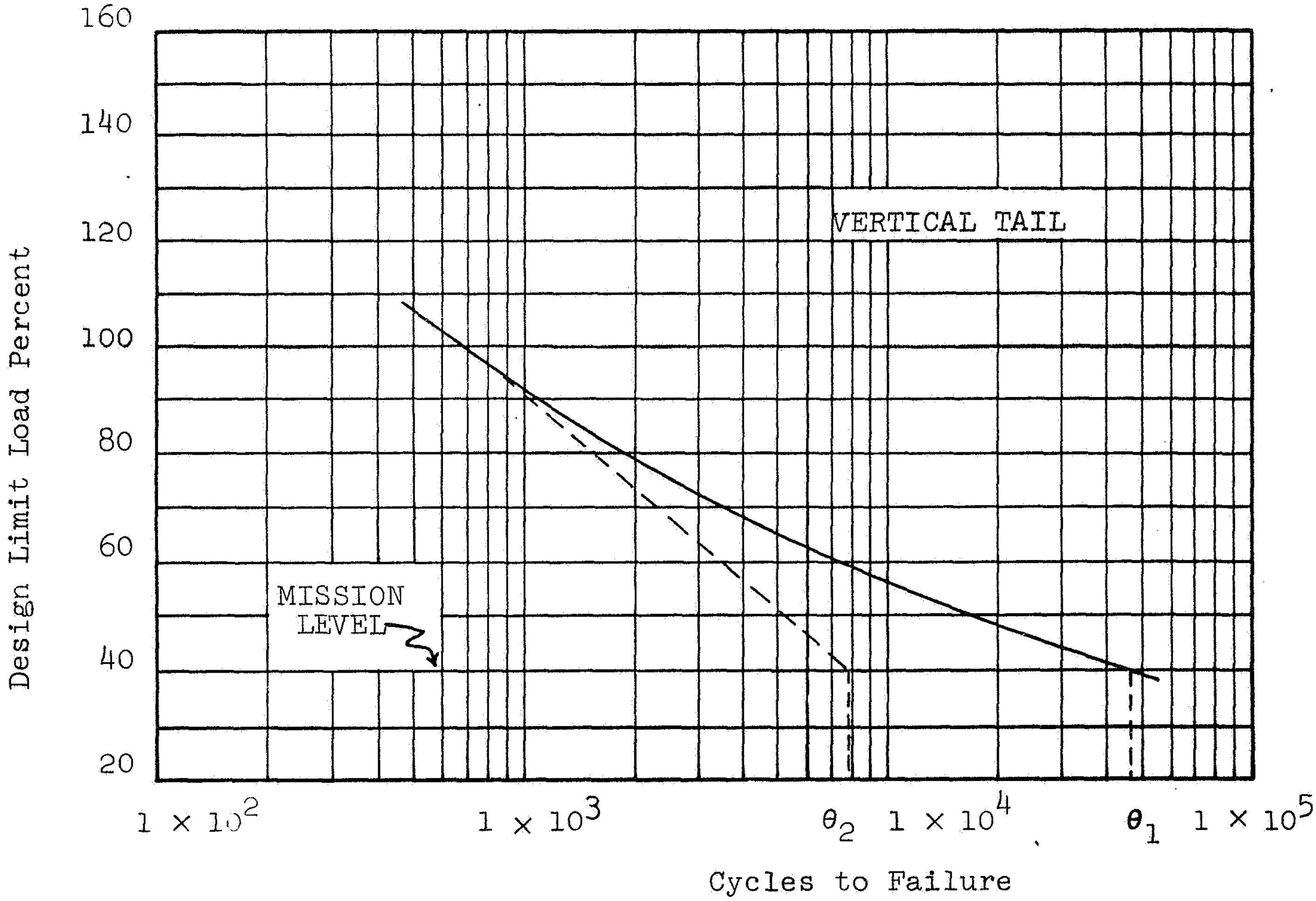
"Shock and Vibration Handbook", Harris and Crede, McGraw Hill Book Company, Inc., 1961, Volume II, page 24.

CONSTANT AMPLITUDE FATIGUE TESTS-TO-FAILURE - MAJOR AIRCRAFT COMPONENTS





Cycles To Failure



Test Description

Twenty-six unused fighter aircraft were disassembled into their major components: wing, horizontal and vertical tail surfaces, aft fuselage, and nose and main landing gear. The results shown here are from the tests of the first three assemblies.

The horizontal tail is an all-movable, longitudinal, control surface with a geometry based on a 45° sweep angle at the 25% chord line. The attachment to the fuselage is statically determinate. The all-metal, cantilever, stressed-skin construction is primarily of 7075-T6 aluminum alloy sheet and plate.

The wings were identical, of all-metal, full-cantilever, stressed-skin construction and were integrally attached to the center section of the fuselage. The wings were of a three-spar, two-cell design with zero dihedral and were swept to a 45° angle at the 25% chord line. The wings were constructed primarily of 7075-T6 aluminum alloy extrusion, sheet and plate.

The vertical tail, which has a sweep angle of 45° at the quarter-chord, is of three-cell, two-spar, conventional construction with ribs at an angle of 45° to the quarter-chord and spaced approximately 7 inches apart. The vertical tail is fabricated primarily from 7075-T6 aluminum alloy sheet and extrusion.

An additional 16 horizontal tail surfaces were made available for testing. Twenty-four of the horizontal tail surfaces, 12 of the wings, and 8 of the vertical tail surfaces were used for the constant amplitude fatigue tests.

The loads were applied hydraulically and distributed through wiffle trees and tension pads to the skin to simulate the load distribution. Load cycling was automatically controlled by means of microswitches installed on dynamometers. Actuation of a switch controlled the operation of a hydraulic by-pass valve permitting the load to build up or fall off.

The load frequency was dependent upon the magnitude of the structural deflection for the load applied. For the wing, the frequency varied from 3 cpm at limit load to 10 cpm at 40% of limit load. The horizontal tail load frequency varied from 3 cpm at 150% limit load to 45 cpm at 40% limit load. Similar frequency ranges were used for the vertical tail tests.

The minimum load for the wing tests was established at 1 g (13.33% of design limit load) which is the normal, unaccelerated flight load for the airplane. The maximum loads applied to the wings ranged from 40 to 120% of design limit loads; the 100% level corresponds to 7.5 g's. The static strength of this type of wing as determined by manufacturers' tests corresponds to 183% of the design limit load.

The horizontal test specimens demonstrated a static strength of 176% of limit load in the manufacturer's static tests. The minimum load for all tests of both the horizontal and vertical tails was arbitrarily set at 13.33% of limit load to obtain data comparable to those from the wing tests. The maximum loads applied to the horizontal tail ranges from 40 to 150% of limit load.

For the tests of the vertical tail, the maximum load ranged from 40 to 100% of limit load. The vertical tail static strength as indicated by the manufacturer's static tests was approximately 176% of limit load. For the tests, the vertical tails were mounted in a support jig which closely matched the spring constant of the fuselage in the vicinity of the attachment fittings.

Data

The data were obtained from tables in the report written on these tests and consisted of cycles to failure at various stress levels (in this case percent of design limit load). The mean values of these data are given in the following table:

Components	Percent of Design Limit Load	Mean Cycles-to-Failure	No. Samples
Wing	120 100 80 60 40	760 2,108 5,241 26,923 149,922	2 4 2 2 2
Horizontal Tail	150 125 100 80 60 40	204 433 1,526 3,847 10,073 55,952	2 2 6 4 6 6
Vertical Tail	100 80 60 40	712 1,639 10,556 45,022	2 2 2 2

Types of Failures

A. Horizontal Tail

Failures occurred at the fuselage attachment and were almost identical.

B. Wing

Failures occurred at 4 different places. Ten of the 12 failures occurred at 3 different wing-fuselage attachments and 7 of the 10 occurred at the same attachment.

C. Vertical Tail

All failures were similar and occurred at the upper end of the attachment of the rear spar to the fuselage attachment fitting.

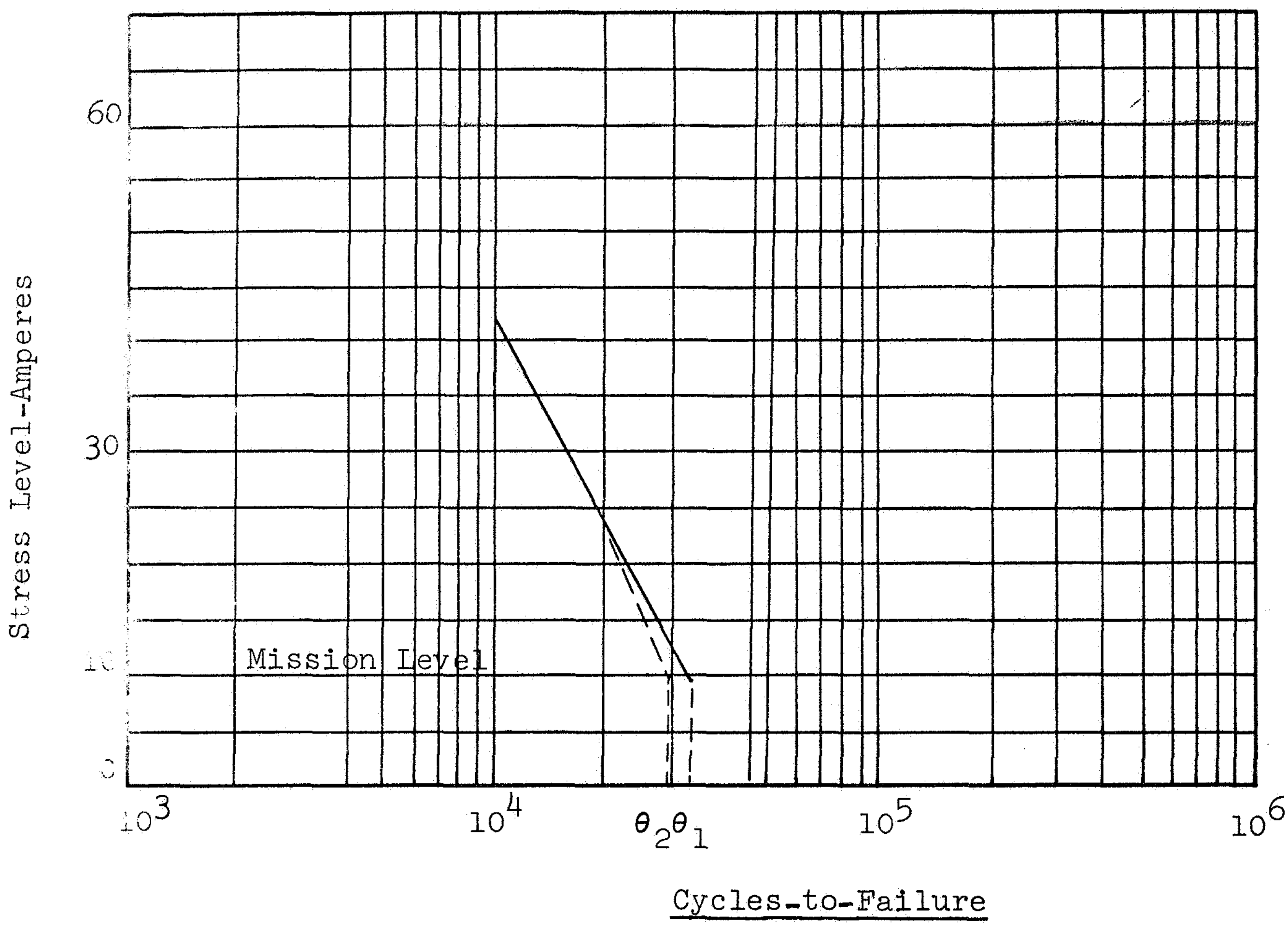
Results

	Horizontal Tail	Wing	Vertical Tail
θ_1	55.95×10^3 cycles	149.92×10^3 cycles	45.02×10^3 cycles
θ_2	5.59×10^3 cycles	44.98×10^3 cycles	8.11×10^3 cycles
θ_1/θ_2	10.0	3.34	5.55
T_1	4.48×10^5 cycles	11.99×10^5 cycles	3.60×10^5 cycles
T_2	2.55×10^3 cycles	11.47×10^3 cycles	9.40×10^3 cycles
T_1/T_2	175.7	104.5	38.3

Reference

"Aircraft Structural Fatigue Research in the Navy", M. S. Rosenfield, ASTM Special Technical Publication No. 338, 1963.

TEST-TO-FAILURE
ELECTRO-MECHANICAL LIMIT SWITCH



Test Description

This test was conducted for the Rome Air Development Center. The test consisted of cycling the limit switch until it failed, first by cycling the switch for a period of continuous energized operation followed by cycling the switch until failure by mechanical forced operation. Tests were conducted at the 10-amp, 30-amp and 60-amp levels. At the 10-amp level, 30,000 cycles of electromechanical operations were completed followed by 20,000 cycles of mechanical operation. At the 30-amp level, the limit switches were operated electro-mechanically for 20,000 cycles followed by 10,000 cycles of mechanical operation and at the 60-amp level the limit switches were limited to 6,000 cycles, followed by 4,000 cycles of mechanical operation.

Data

The data used in the above graph were obtained from a plot of test results. The tests began with a specified number of samples and were discontinued after a specified percentage had failed. The mean cycles-to-failure of only those samples which failed are used in this comparison and shown in the table:

Amps	Mean Cycles-To-Failure	No. of Samples
60	6,062	8
30	16,318	11
10	34,167	6

Types of Failures

All failures were either mechanical or were caused by gumming of the contact points. Differentiation was not made between failure modes.

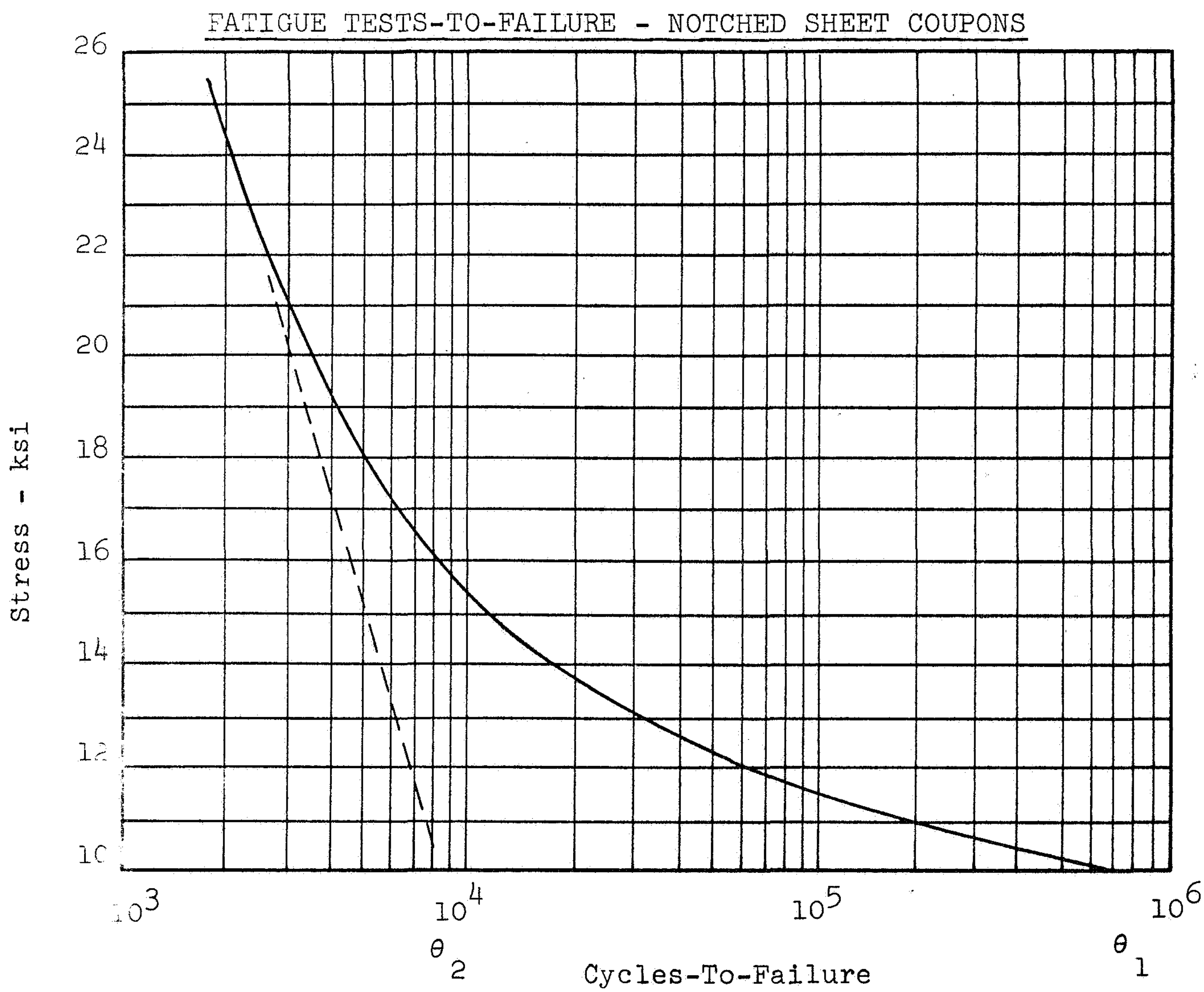
Results

$\theta_1 = 34{,}167$ cycles; $\theta_2 = 31{,}580$ cycles; $\theta_1/\theta_2 = 1.082$

$T_1 = 273{,}336$ cycles; $T_2 = 89{,}520$ cycles; $T_1/T_2 = 3.053$

Reference

"Electro-mechanical Component Reliability", May 1963, RADC-TDR-63-295.



Test Description

Fatigue tests-to-failure were run on simple notched sheet coupons of 7075-T6 aluminum alloy. These tests were run using a sinusoidal loading pattern of constant peak amplitude and a mean stress of -10 ksi.

A magnetic-tape-controlled fatigue-loading machine was assembled from available equipment. The system consisted essentially of a magnetic tape playback unit, associated electronic amplifiers, calibration equipment, load monitoring tape recording system, and an oscillograph. The amplified magnetic tape load-demand signal was fed through a summing junction to a highly sensitive electrohydraulic servo-valve which controlled the pressure on each side of a 17,000 lb.-capacity, double-acting, hydraulic loading jack. The fatigue test specimen was coupled in series to the hydraulic jack, through a calibrated electrical strain-gage load-measuring cell.

The test specimens were 3 inches wide and 0.040 inch thick. A theoretical elastic stress concentration factor of 7 was achieved by drilling a series of central holes in the specimens tested. Floating edge-grooved stiffener blocks were installed to prevent buckling under the maximum compressive loads.

Data

The data were taken from a table of results presented in the test report and consisted of number of cycles-to-failure as a function of the stress amplitude (S-N curves). The mean values of the number of cycles to failure are given in the following table:

Stress Amplitude ksi	Number of Cycles-to-Failure	No. of Samples
25	1,980	5
20	3,179	5
15	14,400	5
12.5	35,904	5
10	814,088	5

Results

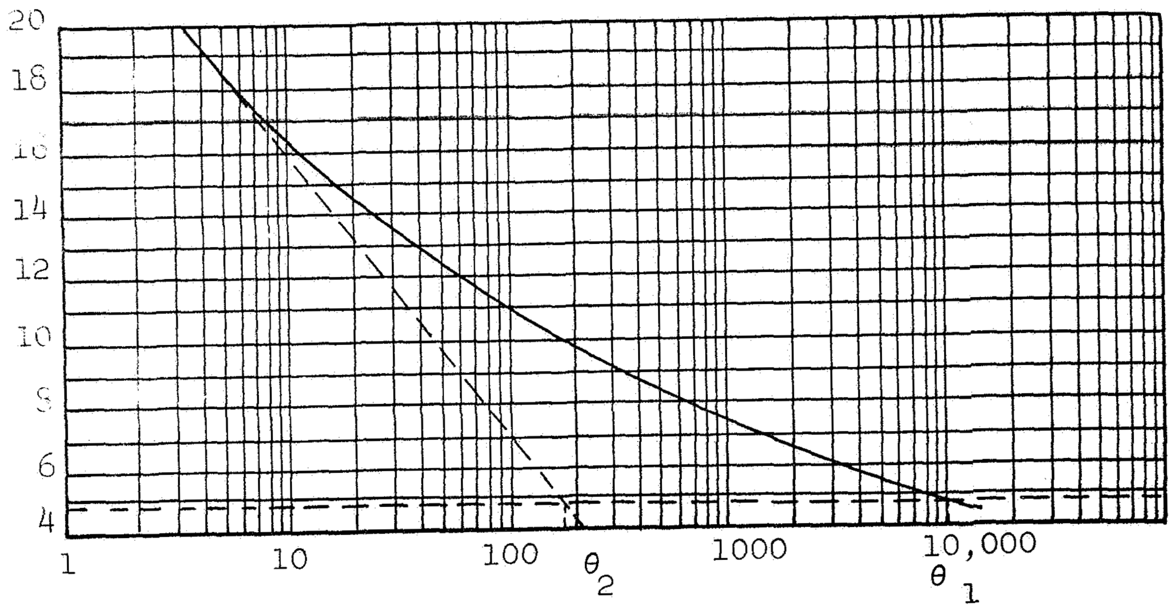
θ_1 = 814,088 cycles; θ_2 = 8,195 cycles; θ_1/θ_2 = 99.3396

T_1 = 6,512,700 cycles; T_2 = 20,636 cycles; T_1/T_2 = 315.599

Reference

"An Engineering Evaluation of Methods for the Prediction of Fatigue Life in Airframe Structures", Crinchlow, W. J.; McCulloch, A. J.; Young, L.; and Melcon, M. A., Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, Technical Report No. ASD-TR-61-434, March 1962, p. 271.

AXIAL LOAD FATIGUE TESTS TO FAILURE - ADHESIVE BONDED JOINTS



Test Description

The data shown were obtained from axial loading fatigue tests of single adhesive bonded lap-joints. The length of the joint overlap was 1/2 inch and the width was 1/2 inch. The material tested was 0.063 inch thick clad 2024-T3 aluminum alloy. The adhesive was a vinyl-phenolic type FM-47 liquid film system. All joint specimens used were prepared by the Plastic and Composite Branch, Nonmetallic Materials Laboratory, ASD. The metal surface preparation and bond cures for all test specimens were the same as those used when the adhesive was qualified under MIL-A-5090B. According to the standard bonding procedure, the adhesive bonded joints were reinforced with glass fibers for higher cohesive strength of the bonding.

The tests were conducted on a constant frequency type, 300 kg., Schenck fatigue-testing machine at a frequency of 3600 cpm with the ratio of minimum-to-maximum stress being R = 0.10. The specimens were clamped at one end to the load transmitting side and at the other to the dynamometer. The dynamometer was comprised of a calibrated steel ring and reading microscope. The deflection of the ring dynamometer was measured with the microscope, which had a magnification of 250X. A constant amplitude cyclic load was applied and maintained accurately to within 1 to 3% of the maximum load.

Data

The data presented were taken from a table of results in the report of these tests and consist of kilocycles-to-failure at various stress levels. The mean values of these cycles-to-failure are given in the following table:

Repeated Stress of Sheet - Max. psi	Mean of Kilocycles-to-Failure	Number of Samples
19,250	3.66	3
16.200	8.30	3
12,550	42.3	3
9,520	231	3
6,660	2,002	1
6,540	901	1
4,760	12.060	2

On the plot of these results the lower case points at 6,660 psi and 6,540 psi were not considered statistically significant because only one sample was tested at each of these stress levels.

Types of Failure

All of the specimens tested failed in the FM-47 bonding. The adhesive debonded, and some of the glass fibers fractured.

Results

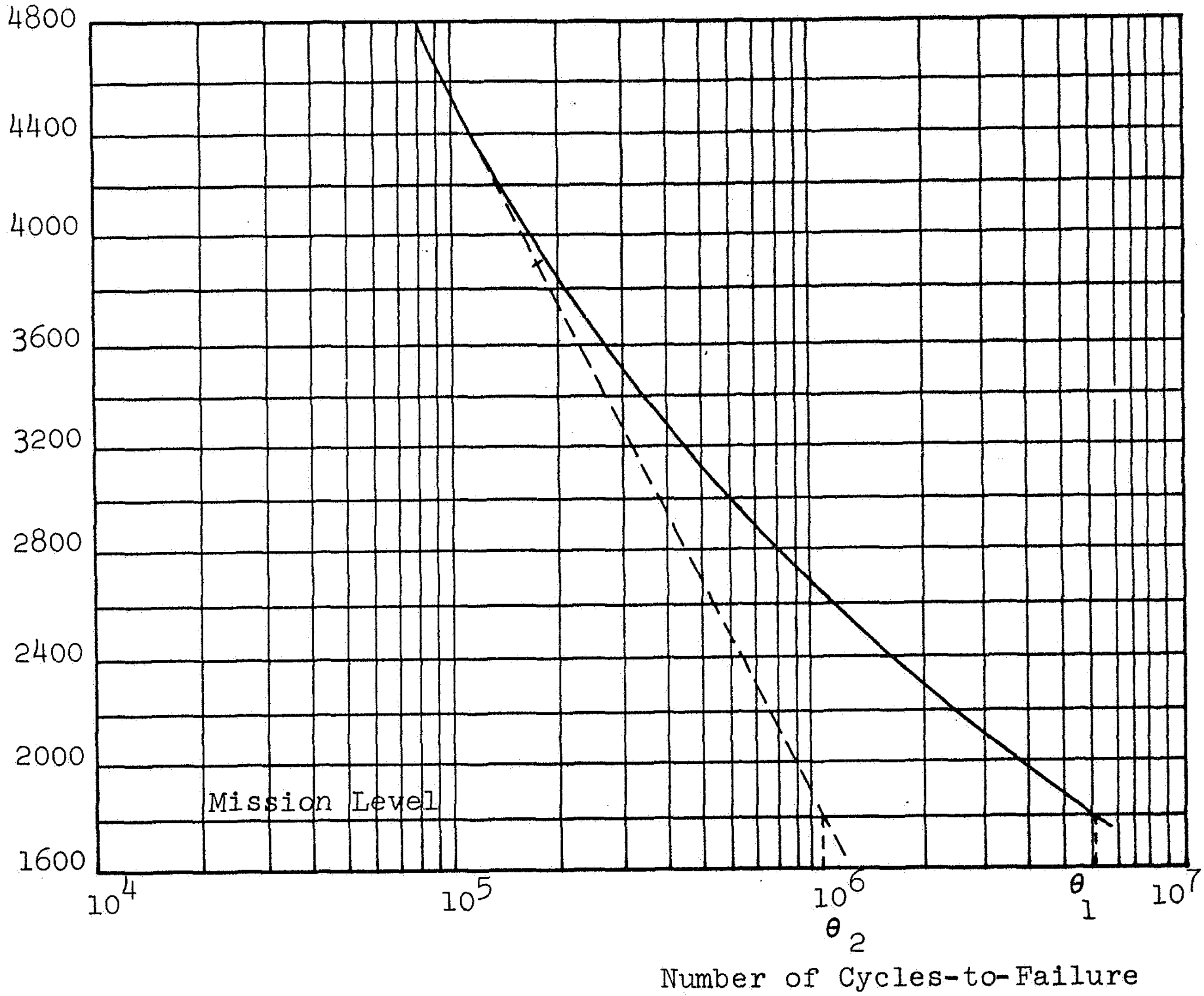
$\theta_1 = 12,060$ Kilocycles; $\theta_2 = 186.1$ Kilocycles; $\theta_1/\theta_2 = 6,480$

$T_1 = 96,480$ Kilocycles; $T_2 = 47.84$ Kilocycles; $T_1/T_2 = 2,016$

Reference

"The Effect of Stress Distribution on the Fatigue Behavior of Adhesive Bonded Joints", D. Y. Wang, Technical Documentary Report No. ASD-TDR-63-93, July 1963.

FATIGUE TESTS-TO-FAILURE - L65 LUGS



Test Description

Nine AWA L.A. L65 lugs were tested-to-failure. The stress cycles were completely reversed. The lugs were not bushed nor were interference fits used.

Data

The data presented here were taken from a plot in the referenced work. These data consisted of the number of cycles-to-failure at various stress levels (psi). The mean number of cycles-to-failure at the respective stress levels are given in the following table:

Net Alt. Stress psi	Mean Number of Cycles-to-Failure	Number of Samples
4750	84,000	4
3900	175,000	2
1800	5,600,000	3

Results

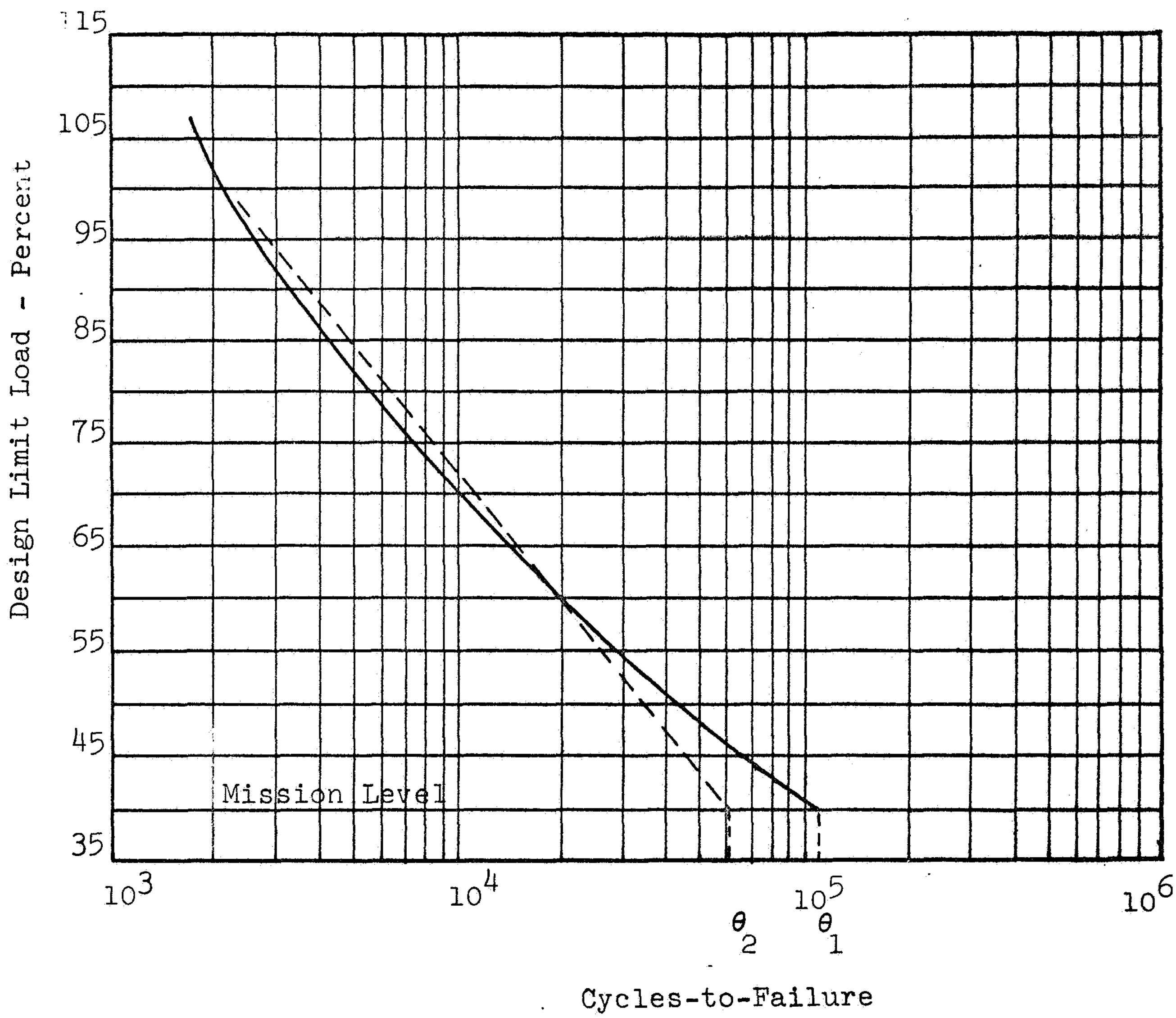
$\theta_1 = 5.6 \times 10^6$ cycles; $\theta_2 = 1.07 \times 10^6$ cycles; $\theta_1/\theta_2 = 5.23$

$T_1 = 4.480 \times 10^7$ cycles; $T_2 = 1.036 \times 10^6$ cycles; $T_1/T_2 = 43.24$

Reference

"Fatigue Lessons Learnt From the Argosy", Troughton, A. J., Rymand, R. J., and McClellan, G., A lecture given by A. J. Troughton to the ICAF/AGARD Fatigue Symposium Paris on 17 May 1961, Proceedings of Symposium on Fatigue of Aircraft Structures, Paris, May 16-18, 1961, The MacMillian Company, New York, N. Y., 1963.

FATIGUE TEST-TO-FAILURE -
COMPOSITE BEAM



Test Description

The specimens tested were 49-inch long, composite beams which consisted of two 1 1/2 by 5/8 by 1/8-inch channels and two 1/4 by 2-inch strips, all of 7075-T6 aluminum alloy. A 5/8 by 3/4-inch steel splice bar separated the two channels and was symmetrically positioned with respect to the median plane of the specimen. The beam specimens were fabricated in accordance with conventional aircraft manufacturing practices by the Aeronautical Structures Laboratory of the Naval Air Material Center in Philadelphia. The specimens were believed to have been fabricated from different batches of material. A pneumatic cylinder was used to apply loads at frequencies of about 15 to 40 cpm, depending on the amplitudes of the loads. This cylinder applied the loads transversely to the center of the simply supported beam. The simple supports were bearings and flexure plates which provided rotational and translational freedom, respectively. The flexure plates introduced a longitudinal stress of 100 psi into the specimen when a transverse load of 5,000 lb was applied. The effective length of the beam specimen from bearing to bearing was 53 inches. The load was applied to the specimen by a pin passing through a snug fitting hole in the loading fixture and the specimen. The faces of the loading and support fixtures which contact the specimen are serrated to prevent impacting and fretting of the specimen in load cycles which pass through zero. Two dynamometers were inserted between the piston pod of the pneumatic cylinder and the specimen. One of these monitored the maximum and minimum load as they were applied; the other served as a load-sensing element. Static tests were made on two specimens from each of the three specimen shipments. Limit load was calculated by applying a 1.5 factor of safety to the measured static-strength values. In each test the load was cycled between a constant predetermined load level and 14.3% of limit load.

Data

The data were taken from the published test report and consisted of the times-to-failure at various stress levels expressed in percent of design limit load. The mean values of the number of cycles-to-failure are given in the following table:

Design Limit Load Percent	Number of Cycles to Failure	Number of Samples
100	2,200	4
80	6,300	2
60	11,900	3
40	85,700	2

Types of Failure

Nearly all failures occurred at the center of the specimen or at one rivet spacing away from the center. Frequent inspections usually did not reveal the presence of fatigue cracks prior to failure. In the few cases where cracks were detected, at least 93% of the ultimate life had elapsed.

Results

$\theta_1 = 85,700$ cycles; $\theta_2 = 51,910$ cycles; $\theta_1/\theta_2 = 1.651$

$T_1 = 685,600$ cycles; $T_2 = 34,040$ cycles; $T_1/T_2 = 20.141$

Reference

"Programmed Maneuver-Spectrum Fatigue Tests of Aircraft Beam Specimens", Mordfin, L., Halsey, N. Symposium on Fatigue Tests of Aircraft Structures Low-Cycle, Full-Scale, and Helicopters, ASTM Special Technical Publication No. 338, October 1962, pp. 251-272.